

The Age of the HD 15407 System and the Epoch of Final Catastrophic Mass Accretion onto Terrestrial Planets around Sun-like Stars

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ABSTRACT

From optical spectroscopic measurements we determine that the HD 15407 binary system is ~ 80 Myr old. The primary, HD 15407A (spectral type F5 V), exhibits strong mid-infrared excess emission indicative of a recent catastrophic collision between rocky planetary embryos or planets in its inner planetary system. Synthesis of all known stars with large quantities of dust in their terrestrial planet zone indicates that for stars of roughly Solar mass this warm dust phenomenon occurs at ages between 30 and 100 Myr. In contrast, for stars of a few Solar masses, the dominant era of the final assembling of rocky planets occurs earlier, between 10 and 30 Myr age. The incidence of the warm dust phenomenon, when compared against models for the formation of rocky terrestrial-like bodies, implies that rocky planet formation in the terrestrial planet zone around Sun-like stars is common.

Subject headings: circumstellar matter — infrared: planetary systems — planets and satellites: formation — stars: individual (HD 15407A, HD15407B) — stars: kinematics and dynamics

1. Introduction

Investigating the formation of terrestrial planets outside of the Solar System can give insight into the origin of the Earth-Moon system and whether similar planetary system

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architectures form around other stars. The study of extra-solar terrestrial planet formation must currently be carried out through indirect searches for the dusty aftermath of formation events. Since the dust is located in the terrestrial planet zone, it will have temperatures of ~ 300 K and will emit most of its thermal radiation at ~ 10 μm . Stars actively undergoing terrestrial planet formation will have substantial amounts of warm dust orbiting in their terrestrial planet zones and will thus show mid-infrared emission in excess of what one would expect from the star alone. Properly establishing the age of such mid-infrared excess systems is necessary for comparison with expectations from planet formation theories and simulations.

We were alerted to excess mid-infrared emission around the star HD 15407A through a paper entitled “Detection of silica dust in the debris disk around HD 15407” presented at an October 2009 Spitzer meeting by H. Fujiwara (E. Becklin, personal communication 2009). At this meeting, the age for HD 15407A was suggested to be ~ 2 Gyr. We felt this age could be in error, and initiated our own follow-up observations to independently constrain HD 15407A’s age. Here we report these observations, our revised value for the age of the HD 15407 binary system, and a discussion of terrestrial planet zone collisions around adolescent Solar mass stars.

2. Observations

Both components of the HD 15407 system were observed in cloudy conditions at Mauna Kea Observatory with the Keck I telescope and HIRES echelle spectrometer (Vogt *et al.* 1994). With the HIRES red collimator wavelengths between 4680 and 8700 \AA were covered at a resolution of 50,000 (as determined from the FWHM of single ThAr arc lines). The final signal-to-noise ratio per pixel, measured at 6700 \AA , is 350 for HD 15407A and 200 for HD 15407B. Spectral data were reduced and extracted using both the *MAKES* software package and standard IRAF tasks and echelle reduction procedures.

3. Results

3.1. HD 15407 Stellar Parameters

Our star of interest, HD 15407A, is part of a visual double star system. Table 1 contains information about HD 15407A, the dusty primary star, and HD 15407B, the secondary component of the HD 15407 system. For both stars we employ line-depth ratios to roughly determine absolute temperature and, for HD 15407B, luminosity. Those interested in the

details of determining such parameters are referred to Melis *et al.* (2009).

We deduce that HD 15407A has a temperature similar to that of an F5-type star; its broad-band colors (BVIJHK_s) are in agreement with this temperature class determination. This suggests that HD 15407A is not significantly reddened by its circumstellar material and we adopt a temperature class of F5±1 subclass. Spectral analysis suggests that HD 15407B is a dwarf star with a temperature class of K3±1 subclass and an effective temperature of 4600 K. Broad-band colors for HD 15407B instead suggest that this dwarf star has an earlier spectral type of K0-K1. We adopt a spectral type of K2 V with an uncertainty of ±1 temperature subclass.

3.2. Excess Infrared Emission from HD 15407A

Excess infrared emission is detected towards HD 15407A by IRAS in the 12 and 25 μm bands (Oudmaijer *et al.* 1992). Archival Spitzer IRS spectroscopy of HD 15407A (AOR 26122496, PI Fujiwara) confirms the excess (see Figure 1). We note the presence of solid state dust emission features in the IRS spectrum. Figure 2 compares the IRS spectrum of HD 15407A with those of other stars that host substantial quantities of terrestrial planet zone dust. We defer quantitative analysis of these spectral features to later publications.

To estimate the dust temperature and the fraction of the stellar luminosity reradiated by the dust ($\tau=L_{\text{IR}}/L_{\text{bol}}$) we fit optical and near-infrared measurements out to K_s-band with a synthetic stellar atmosphere spectrum (Hauschildt *et al.* 1999) and a blackbody to model the dust excess (see Figure 1). In this way we find that the fraction of stellar light reradiated by the circumstellar dust is $\sim 5.7 \times 10^{-3}$ and that the grains radiate with a blackbody temperature of ~ 500 K. Such grains will reside at a distance of ~ 0.8 AU from HD 15407A.

We note that both the IRS spectrum and an IRAS upper limit at 60 μm of 347 mJy (4σ) suggest that there is no cold dust orbiting HD 15407A.

3.3. Age of the HD 15407 System

To determine the age of the binary system we obtained and analyzed high-resolution echelle spectra for both stars and searched for X-ray detections in the literature. From these data we estimate the system age from the lithium content in the stellar photospheres, velocity widths of absorption lines, Galactic space motion, and chromospheric activity; details can be found in Zuckerman & Song (2004). The lithium 6710 Å absorption feature is strongly detected in the spectra of both stars (Table 1 and Figure 3). Lithium content in a stellar

atmosphere is mainly determined by the star’s age and mass. These strong detections are consistent with roughly Solar mass stars of ~ 30 -100 Myr age (see Figure 3). We note that the lithium equivalent width (EW) measured for HD 15407A (~ 94 mÅ) is significantly stronger than the range of Li I EWs (~ 40 -70 mÅ) quoted for similar spectral type Pleiads in Figure 3; this suggests that the HD 15407 system may be younger than Pleiades cluster stars.

The ROSAT All-Sky Survey (RASS) detected X-ray emission from HD 15407B. Analysis of this X-ray emission (Table 1 and Figure 4) suggests a star of ~ 100 Myr age (Zuckerman & Song 2004). We note that Suchkov *et al.* (2003) claim a detection of HD 15407A by the RASS. Upon further investigation, it is revealed that the putative detection has an angular separation of $>5'$ from HD 15407A, well outside the RASS positional uncertainties. We conclude that HD 15407A was not detected by ROSAT. We estimate an upper limit for its fractional X-ray luminosity in the following manner: HD 15407B is detected by ROSAT with $\sim 4\sigma$ significance. We take this level of X-ray flux as our upper limit for HD 15407A. Thus, we derive the upper limit to HD 15407A’s fractional X-ray luminosity by scaling HD 15407B’s fractional X-ray luminosity by the ratio of the two star’s total luminosities. This upper limit is reported in Table 1 and plotted in Figure 4 where it is shown to be consistent with stars of ~ 100 Myr age.

Velocities of the HD 15407 system toward the center of our Milky Way galaxy, around the Galactic Center, and perpendicular to the Galactic plane (U, V, W) are calculated from Table 1 sky positions and proper motions, the Hipparcos measured distance (van Leeuwen 2007, where we assume HD 15407A and B are bound as is suggested by their common proper motions and the optical echelle measured radial velocities, see Table 1), and heliocentric radial velocities. UVW is computed for each component of the HD 15407 system and these two results are averaged together to produce the values reported in Table 1. Comparison of these computed UVW space motions to those of known nearby stellar associations (see Figure 3 and e.g., Zuckerman & Song 2004; Torres *et al.* 2008, and references therein) suggests that the HD 15407 system is a member of the AB Dor moving group (UVW $\sim -8, -27, -14$ km s $^{-1}$). The distance to the HD 15407 system and its position in the plane of the sky are consistent with it being a member of the AB Dor moving group (e.g., see Table 5 of Zuckerman & Song 2004). Age estimates for the AB Dor moving group range from ~ 50 -120 Myr (Zuckerman *et al.* 2004; Luhman *et al.* 2005; Torres *et al.* 2008, and references therein).

Based on the above analysis, we suggest a best estimate age for the HD 15407 system of ~ 80 Myr with a conservative range of plausible ages from 60-120 Myr. We note that the measured $v \sin i$ for HD 15407B¹, ~ 4 km s $^{-1}$, is surprisingly low for a star of such age and

¹ $v \sin i$ for both stars was measured from the full-width at half-maximum depth (FWHM) of single ab-

spectral type (Zuckerman & Song 2004, and references therein); it is possible that we view HD 15407B in a pole-on geometry.

4. Discussion

Here we use our age estimate for the HD 15407 system to help constrain the era of rocky planet formation in the terrestrial planet zone around stars of Solar mass. We consider stars with fractional infrared luminosities $\tau \gtrsim 0.01$ as very dusty and likely to have undergone a recent collision between two planetary embryos or planets such as that postulated to have formed Earth’s Moon. Rhee *et al.* (2008) considered this problem, but included the very dusty G-type star BD+20 307 in their analysis. Subsequent to their paper, it was discovered that BD+20 307 is an old main sequence star and hence its circumstellar dust is not related to terrestrial planet formation (Weinberger 2008; Zuckerman *et al.* 2008). Rhee *et al.* (2007) and C. Melis *et al.* (2010, in preparation) have investigated “intermediate mass” stars (spectral types late-B through early-F and masses from ~ 8 to $\sim 1.5 M_{\odot}$) with large masses of warm dust in their terrestrial planet zones. The half dozen or so very dusty intermediate mass stars currently known have ages between 10 and 30 Myr. This suggests that for such stars the era of most intense accretion of material onto rocky planets is over by about 30 Myr. Such a conclusion is similar to that drawn by Currie *et al.* (2008) who considered an ensemble of young intermediate mass stars but with only modest amounts of warm dust. We now show that the corresponding era for solar-mass stars, by contrast, lasts for ~ 100 Myr.

Based on IRAS and Spitzer surveys we are aware of four adolescent Solar-type stars with $\tau \gtrsim 0.01$: AB Dor member HD 15407A (this paper); Pleiades member HD 23514 (Rhee *et al.* 2008); M47 member P1121 (Gorlova *et al.* 2004); and NGC 2547 member ID8 (Gorlova *et al.* 2007). The ages of these stars range between 35 Myr (NGC 2547) and about 100 Myr (the other 3 stars). Interestingly, two of the four young, very dusty Sun-like stars mentioned above are in wide binary systems (HD 23514, D. Rodriguez *et al.* 2010 in preparation; HD 15407, this work). The other two systems (ID8 and P1121) have not been exhaustively searched for binary companions; confirmation of any such binarity would be suggestive (although still in the realm of statistics of small numbers) of a link between binarity and catastrophic terrestrial planet collisions.

We note the relative absence of similar numbers of warm dust stars with ages from

sorption lines in the Keck HIRES spectra; the intrinsic FWHM resolution for the HIRES setup used was $\sim 6 \text{ km s}^{-1}$, a value we subtract in quadrature from the FWHM measured in the spectra when determining $v_{\text{ sini}}$ (see Equation 6 in Strassmeier *et al.* 1990).

~ 200 to 800 Myr. No stars in four stellar associations with ages in this range – the Hyades (Cieza *et al.* 2008), Praesepe (Gáspár *et al.* 2009), Carina-Near (Zuckerman *et al.* 2006), and Ursa Major (King *et al.* 2003) – have substantial quantities of warm dust in their terrestrial planet zone. Together these four groups contain ~ 200 Solar-type stars. In the field, IRAS has surveyed many more stars with ages of ~ 200 to 800 Myr compared to the 30 to 100 Myr range, yet none in the former age range have been identified with luminous warm dust.

We estimate the frequency of catastrophic accretion events during rocky planet formation in the terrestrial planet zone by considering the detection rate of very dusty stars in the field and in young clusters. Very dusty nearby field stars were better investigated in the all-sky IRAS survey than with Spitzer’s pointed capabilities. As noted by Rhee *et al.* (2008), IRAS could have detected a main sequence dwarf with $\tau \gtrsim 0.01$ and spectral type between F4 and K0 out to about 150 pc. There are 400 or so such field stars with ages ~ 100 Myr that IRAS could have detected, but of these, only HD 15407A has sufficient dust to actually have been detected by IRAS. Similarly, among the young clusters studied with Spitzer – NGC 2232 (Currie *et al.* 2008), M47 (Gorlova *et al.* 2004), NGC 2547 (Gorlova *et al.* 2007), IC 2391 (Siegler *et al.* 2007), and the Pleiades (Stauffer *et al.* 2005; Gorlova *et al.* 2006) – the three very dusty cluster stars listed previously represent about one Solar-type star in 200 (roughly consistent with the determination for Solar-type cluster stars by Balog *et al.* 2009).

Thus, the high τ warm dust phenomenon manifests itself at about one adolescent Solar-type star in 300 . If all F4-K0 stars display this phenomenon as adolescents, then the lifetime of the phenomenon at a typical Sun-like star is about $300,000$ years.

To understand this frequency of the warm dust phenomenon we consider a dust production model similar to that described by Rhee *et al.* (2008) for HD 23514. Rhee *et al.* (2008) analyzed existing observations through October 2007 with the aid of a model of colliding planetary embryos due to C. Agnor and E. Asphaug (Agnor *et al.* 1999; Agnor & Asphaug 2004; Asphaug *et al.* 2006) and earlier researchers. The idea is that following a catastrophic collision of two rocky planetary embryos or planets, fragmented debris covering a range of sizes goes into orbit around a central star. Rhee *et al.* (2008) assumed that collisions between debris would be frequent enough to establish an equilibrium size distribution where the number of particles of radius “ a ” is proportional to $a^{-3.5}$. In this situation, both the mass carried by particles of radius a and the collision time are proportional to the square root of a . Most of the mass is carried by large fragments while small particles are responsible for most of the excess infrared luminosity and collide the fastest. The radius of the smallest dust particles in orbit around a very dusty star is set by radiative blowout and, for HD 15407A, will be $\sim 1 \mu\text{m}$. The collision time for such particles will be about 1 year divided

by $10 \times L_{\text{IR}}/L_{\text{bol}}$ or ~ 10 years. If the largest initial fragments of a catastrophic collision have radii ~ 100 m, then their collisional lifetime is $\sim 100,000$ years which is within a factor of 3 of the lifetime (estimated in the previous paragraph) required if all Solar-type stars are forming rocky planets in their terrestrial planet zone. Should the formation of rocky terrestrial planets involve more than a single catastrophic collision, then the model-estimated warm dust phenomenon lifetime could be more than 100,000 years at each Sun-like star. As noted by Rhee *et al.* (2008), the total mass lost over this interval of time – due to a collisional cascade followed by radiative blowout – will be about the mass of Earth’s Moon.

5. Conclusions

Based on Keck HIRES optical spectroscopy, X-ray flux, and Galactic UVW space motions we estimate the age of the HD 15407 binary system to be ~ 80 Myr and identify the system as likely belonging to the AB Dor moving group. Collecting the full sample of known very dusty debris-disk hosting stars, we find that the era of final catastrophic mass accretion for rocky planets around stars of roughly Solar mass occurs later than around intermediate mass stars. Provided that rocky planet formation in the terrestrial planet zone of most Solar mass stars is accompanied by at least one and possibly a few catastrophic collisions of planet-size objects within a 100 Myr interval, then the detection rate and age range of very dusty Solar-type stars – observed to be about one in 300 for ages between 30 and 100 Myr – can be accounted for. Our conclusion is that existing observations of such dusty stars indicates that most Sun-like stars are accompanied by rocky planets in the terrestrial planet zone and that collisions among such forming planets will occur, as is expected in theoretical simulations of planetary origins.

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Facilities: IRAS (), Keck:I (HIRES), Spitzer (IRS)

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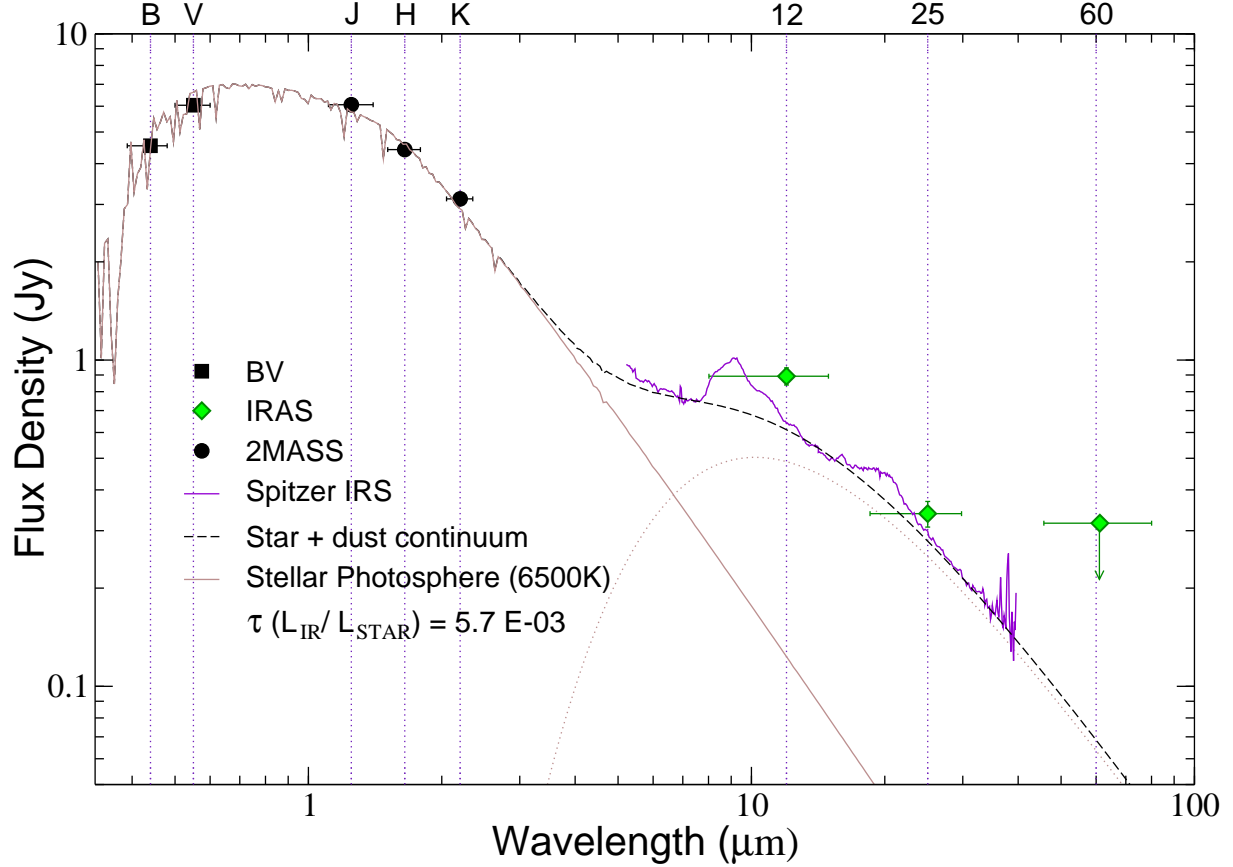


Fig. 1.— Significant mid-infrared excess emission is detected towards HD 15407A. The solid brown curve is a synthetic stellar spectrum (Hauschildt *et al.* 1999) for a 6500 K effective temperature star. The brown dotted curve represents a dust continuum emission blackbody fit to a dust temperature of 500 K. The black dashed line, the sum of the above two curves, is a reasonable fit to all data points. The total luminosity of the excess, determined by integrating under the data points between 1 μm and 100 μm , is $\sim 0.6\%$ of the luminosity of the star. The BV data points are from the Tycho-2 catalog. The green data points are from the IRAS Faint Source Reject Catalog and have not been color corrected. The horizontal bars indicate the filter bandwidths. Overplotted is the reduced, extracted, calibrated Spitzer IRS spectrum.

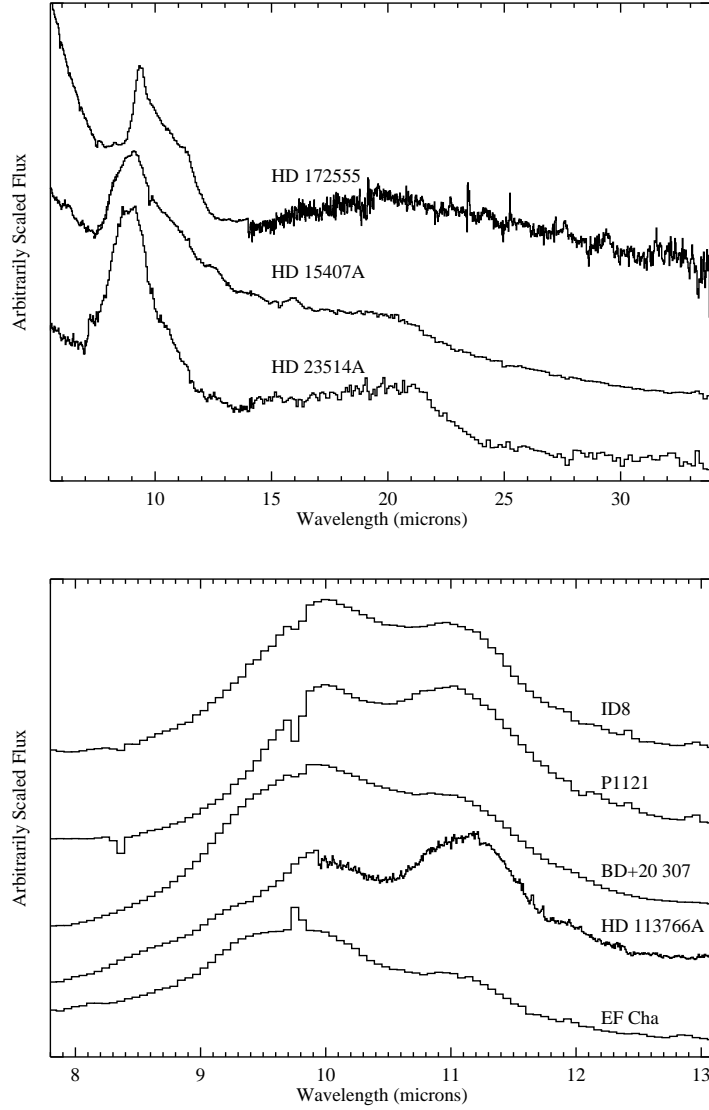


Fig. 2.— *Top Panel:* Comparison of HD 15407A’s IRS spectrum to those of other stars that host $9\ \mu\text{m}$ spectral features. HD 15407A ($\tau \sim 0.6\%$) and HD 23514A ($\tau \sim 2\%$; see Rhee *et al.* 2008, D. Rodriguez *et al.* 2010 submitted) are ~ 100 Myr old mid-F type stars while HD 172555 ($\tau \sim 0.08\%$) is a ~ 12 Myr old late-A type star. HD 172555’s IRS spectrum has been analyzed in great detail and is dominated by features from amorphous olivine and pyroxene, crystalline pyroxene, and silica (Chen *et al.* 2006; Lisse *et al.* 2009); the latter dust species is suggested to result from high velocity impacts. *Bottom Panel:* IRS spectra of other hot-dust hosting stars. ID8 ($\tau \sim 2\%$) is a ~ 35 Myr old early-G type star (Gorlova *et al.* 2007), P1121 ($\tau \sim 1\%$) is a ~ 100 Myr old late-F type star (Gorlova *et al.* 2004), BD+20 307 ($\tau \sim 4\%$) is a >1 Gyr old spectroscopic binary composed of two early-G type stars (Zuckerman *et al.* 2008), HD 113766A ($\tau \sim 1.5\%$) is a ~ 16 Myr old early-F type star (Chen *et al.* 2006), and EF Cha ($\tau \sim 0.1\%$) is a ~ 10 Myr old late-A type star (Rhee *et al.* 2007). HD 113766A’s IRS spectrum has been analyzed in great detail and is dominated by amorphous olivine and pyroxene features and crystalline olivine features (Chen *et al.* 2006; Lisse *et al.* 2008).

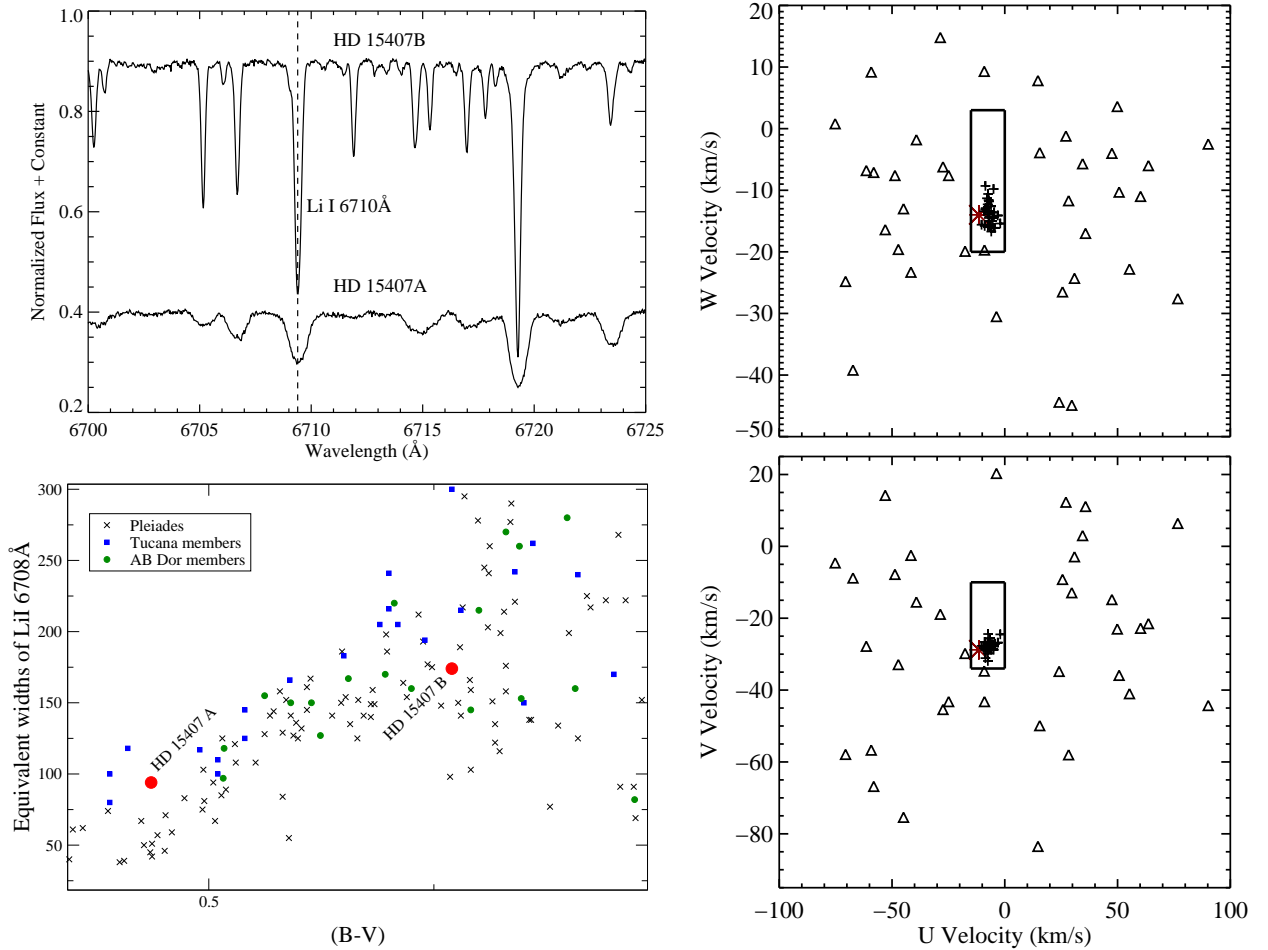


Fig. 3.— *Top Left Panel:* Keck HIRES spectra obtained on UT 29 Nov 2009 and covering the Li I $\lambda 6710$ (vacuum) region for HD 15407A and B. Strong lithium lines are detected in both stars (see Table 1). These spectra are continuum normalized and offset by arbitrary values. Wavelengths in this figure are plotted in the heliocentric reference frame and are in vacuum. *Bottom Left Panel:* Comparison of the measured Li I EWs of HD 15407A and B (Table 1) to those of moving groups with similar age (adapted from Figure 3 of Zuckerman & Song 2004). The Pleiades age is ~ 100 Myr, the Tucana association age is ~ 30 Myr, and the AB Dor association age is ~ 80 Myr (see text and Zuckerman & Song 2004). *Right Panels:* Comparison of the Galactic UVW space motion of the HD 15407 system (red star symbol) with the UVW space motions of (1) the cluster of plus symbols near the center of the figures that are AB Dor moving group members from Zuckerman *et al.* (2004) and (2) triangles that are white dwarfs with mean total ages comparable to that of the Sun (Zuckerman *et al.* 2003; Bergeron *et al.* 2001). The rectangles represent the “good” UVW box for young stars as defined in Zuckerman & Song (2004).

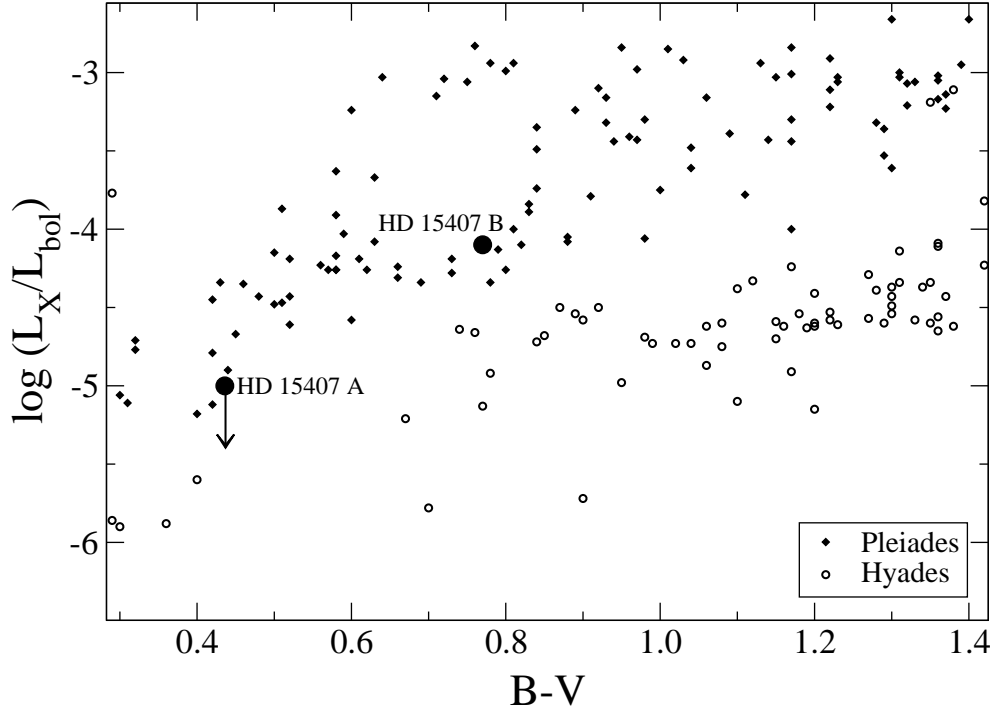


Fig. 4.— Comparison of the calculated fractional X-ray luminosities of HD 15407A and B (Table 1) to those of two clusters of known age (adapted from Figure 4 of Zuckerman & Song 2004). HD 15407A was not detected by the ROSAT satellite, the plotted value is an estimated upper limit (see text). The Pleiades age is ~ 100 Myr while the Hyades age is ~ 600 Myr.

Table 1: Parameters of the HD 15407 binary star system

Individual Stars		
	HD 15407A	HD 15407B
RA (J2000)	02 30 50.65	02 30 48.58
DEC (J2000)	+55 32 54.4	+55 33 06.4
Sp. Type	F5 V	K2 V
Vmag	6.95	9.58
T _{eff} (K)	6500±100	4830±150
pmRA (mas yr ⁻¹)	+80.6 ± 1.0	+83.1 ± 1.0
pmDE (mas yr ⁻¹)	−96.7 ± 1.1	−93.6 ± 1.1
RV (km s ⁻¹)	−10.44 ± 0.39	−10.02 ± 0.17
Li I λ6710 EW (mÅ)	94±4	174±5
<i>v</i> sin <i>i</i> (km s ⁻¹)	20	4
L _x /L _{bol}	<10 ^{−5.0}	10 ^{−4.1}
System		
Distance from Earth (pc)	54.7±2.1	
Separation Between Stars	21.25'' (projected separation of 1160 AU)	
UVW Space Motions (km s ⁻¹)	−11.5, −28.8, −14.0	
Age (Myr)	80 ⁺⁴⁰ _{−20}	

Note. — Epoch J2000 positions are from the 2MASS catalog (Cutri *et al.* 2003). The highest fidelity proper motions come from the Tycho-2 catalog (Høg *et al.* 2000) for HD 15407A and from the UCAC3 catalog (Zacharias *et al.* 2010) for HD 15407B. Radial velocities (RV) for both stars were measured by cross-correlating our HIRES spectra with HIRES spectra of a star from Table 2 of Nidever *et al.* (2002). See the text for discussion of other stellar parameters.